综合考虑抗拔力的土钉支护稳定分析

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摘　要：依据混凝土结构设计规范，考虑面板在冲剪和直剪下的承载力，以及近似考虑面板的抗剪力，设计了6种承载模式，在工程实例的基础上对此进行分析。研究表明，综合考虑各个抗滑力，对于合理确定土钉支护安全系数具有重要意义，可为规范的编制提供参考。

关键词：土钉支护；稳定；抗拔力；冲剪（直剪）破坏

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Stability Analysis of Soil Nail Support Considering Anti-pulling Out Force Synthetically

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Abstract：Judging by design specifications of concrete structure, it considers the panel weight between punching and cutting and panel shearing force, and six modes of weight are designed, which carries on analysis on the base of engineering practice. The research shows that conforming reasonably assurance coefficient of soil nail support has a important significance in view of various skid resistence.

Key words：soil nail support；stability；anti-pulling-out force；punching（cutting）ravage

In recent years，soil nailing is widely used in slopes and pits，its design method is developed and some codes were formed. Stability of soil nailing is a main part of design. However，due to engineering simplicity，the code[1] is not rigorously carried out，especially in internal stability analysis，anti-pulling-out force of nails is not strictly considered，which may causes overestimation or underestimation. Usually，the contribution of the part of length of soil nails in the passive soils is only considered，however，the part of length of soil nails in the passive soils plays great role in the stability of soil-nailed wall，furthermore，linkage strength between soil nails and facing and shear strength of facing itself is often considered infinitely large，while it possibly induces over estimation of the safety factor.

1 Analysis of anti–pulling out force of nails

Anti-pulling out force of nails is mainly decided by three factors，yield limit of steel nail，cohesion between nails and surrounding soils，punching ravage of shotcrete panel due to tensile force at the link position between nails and shotcrete panel. In addition，when anti-pulling out force is considered，the force in the active side should be compared with it in the passive side，furthermore，the anti-punching capability of the shotcrete panel is not clear in the building code, possibly，shear failure of facing will happen if without enough strength. All in all，the anti-pulling out force should be considered synthetically，see figure 1.

From figure 1，anti-pulling out force of nails is determined by four failure modes of nails，and usually in engineering case，kind（3）is considered，especially contribution of the shotcrete panel is neglected，which results in

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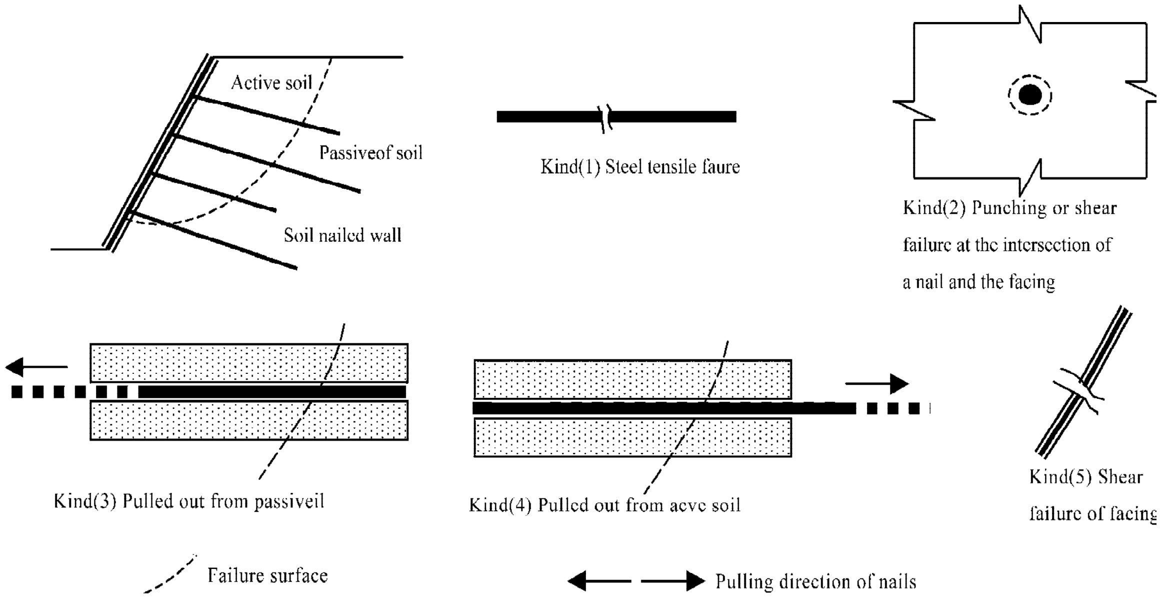


Fig. 1　Failure modes of nails and facing

underestimation or overestimation of anti-pulling out force of nails. Here，punching or shear failure of the joint is considered as a model that a shotcrete plate is under local force vertical to the surface. With consideration of combination of different failure kinds， failure style can be divided to 6 modes:

1）Only considering nails pulled out from passive soils，named as mode A;

2）Only considering nails pulled out from passive soils and active soils，named as mode B;

3） Considering punching or shear ravage of facing，and nails pulled out from passive soil or active soil，named as mode C;

4） Considering punching or shear ravage of facing，yield limit of nails，and nails pulled out from passive soil or active soil，named as mode D;

5）Based on Mode D，furthermore，considering shear strength of facing，named as mode E;

6）Based on Mode A，furthermore，onsidering shear strength of facing, named as mode F;

In《Design standards on concrete structures》[2]， the punching capability of a plate under local force，is given as follows:

$$F_1 \le (0.7\beta_h f_t + 0.15\sigma_{pc,m})\eta u_m h_0 \qquad (1)$$

Hu[3] suggests a simplified approach，

$$F_1 \leqslant 0.7 f_t u_m h_0, \qquad (2)$$

Assume length of a side is a，then

$$F_1 = 0.7 f_t u_m h_0 = 0.7 f_t \times 4\,(a + h_0)h_0, \qquad (3)$$

And capacity of anti-shear of the plate is

$$F_1 = 8 a f_t h_0 \circ \qquad (4)$$

A lower capacity will be selected between computing results of formula（3），（4）. Actually，a nail is inclined to the shotcrete panel usually with an angle about 10° to 20°，with simplicity consideration，the angle is assumed to 90°. Assume thickness of shotcrete panel is 100 mm with concrete grade C20，then its yield limit is 1.10 MPa，assume yield limit of steel nails is 152 kN with diameter 25 mm，through equivalent square area method，the length of a side is 9 mm，through formula（3），（4），the load capacity of joint is 7.92 kN，considering joint between nails and steel of facing，its value is selected as 12.0 kN.

Shear strength of facing is estimated as follows:

$$F_2 = wd\sigma_s, \qquad (5)$$

where w is horizontal spacing of each column of nails，d is thickness of facing，and σ_s is shear strength of facing，usually is $\sigma_c/8$，due to safety factor，value of shear strength is assumed as the same as tensile strength.

2　Search of critical slip surface through chaotic approach

Due to a good number of iteration to locate the critical arc surface，traditional search methods named as numerical methods， here are difficult to deal with the search， non-numerical methods including annealing method， ants method， genetic method[4]，chaotic method[5]，and so on，are widely adopted in optimization，especially in those functions without explicit expression. For example，safety factor of slope stability has no clear expression between the location of critical slip surface. Chaotic method is a random，entire range search method， and it is simple and convenient， which will be used here. Based on circular slip surface, a procedure is built through chaotic approach, which is shown in figure 2.

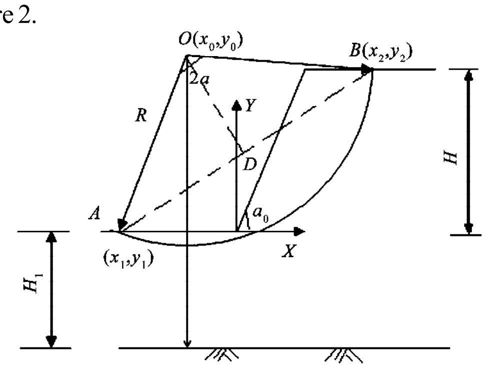


Fig. 2 Determination of arc slip surface through two points and center angle

Where H_1 is the distance between slip toe and rigid rock or soil layer's surface, H is the height of the slope, meaning of other symbols is expressed in the figure.

Linking two intersect points determines line AB, and if the center angle is given, then the arc is got, see formula 5.

$$\begin{cases} \beta = \mathrm{arctg}\dfrac{y_2 - y_1}{x_2 - x_1}; \\ R = \dfrac{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}}{2\sin\alpha}; \\ x_0 = \dfrac{x_1 + x_2}{2} - R\cos\alpha\sin\beta; \\ y_0 = \dfrac{y_1 + y_2}{2} + R\cos\alpha\cos\beta \end{cases} \tag{6}$$

In stability of soil nailing, Fellenius method is often used due to simplicity, which will be adopted in this study, which is shown as follows

$$F_S = \frac{\sum\left[-(W_i + Q_i)\cos\alpha_i\tan\varphi_j + \right.}{\sum\left[(W_i + \right.} \rightarrow$$

$$\leftarrow \frac{\left.\dfrac{R}{S_{hk}}\sin\beta\ \tan\varphi_j + C\dfrac{\Delta_j}{\cos\alpha_j} + \dfrac{R}{S_{hk}}\cos\beta\right]}{\left.Q_i)\sin\alpha_i\right]}, \tag{7}$$

where, w_i is the weight of a slice, Q_i is the sum of surcharge underground and above ground, a_i is the bottom angle of a slice between the local arc part and horizontal level, Φ_j is the friction angle of the j^{th} soil, R_k is the anti-pulling out force of the k^{th} nail, S_{hk} is horizontal distance of two adjacent columns nails, C_j is the cohesion of the j^{th} soil, β_k is the angle between of the k^{th} row nails and tangent line of the local arc part.

3 Cases

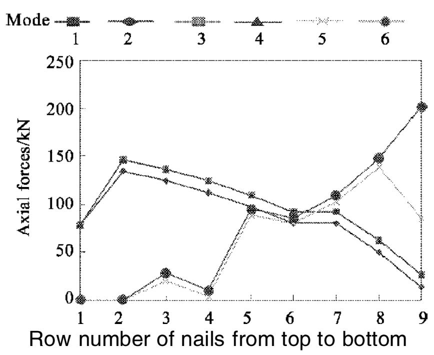
3.1 Case 1

Two cases are studied in this paper in order to verify the necessary of considering anti-pulling out force of nails synthetically. A pit in Beijing, China is anchoring with soils nailing, the depth of the pit is 13.75 m, with a slope of 1 in 0.1 and 1 in 0.2, the soil nailing with a slope of 1 in 0.2 will be studied here and strength parameters of soils underneath are listed in table 1.

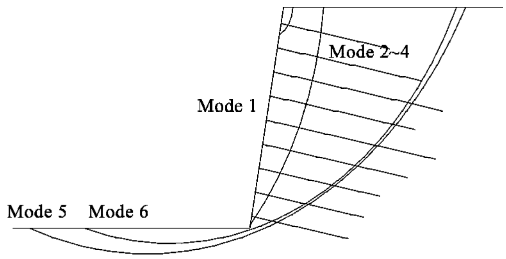
Tab. 1 Strength papmeters of soils of a pit

Soil layer	Distance of the bottom of each soil layer /m	Thickneess of each soil layer /m	Density /(kN · m^{-3})	Friction angle / °	Cohesion /kPa
Mixture filling	-2.5	2.5	20	15	10
Clay silt	-6	3.5	20	23	10
Silty clay	-9	3	20	18	14
Fine sand	-16	7	20	30	0
Clay	-24	8	20	20	10

From top to bottom, in northwest of the pit1-1 with a slope of , length of each row of nails is 9, 12, 14, 12, 14, 10, 9, 8 seperately. Cohesion between each row of nails from top to bottom is 60, 60, 60, 60, 60, 60, 80, 80, 80 kPa separately, anti-pulling-out force of each row of nails is shown in figure 3(a), and from mode 1 to 6, safety factor is 0.92, 0.81, 0.86, 0.86, 1.15, 1.17 separately, location of critical slip surface is drawn in figure 3(b).



a) Distribution of anti–pulling out force of each row of nails represents modes 1 to 6



b)　Location of critical slip surface with different modes

Fig. 3　Computing results of case 1

From figure 3, when neglecting ravage failure of the joint between facing and nails, in other words, the joints are strong enough to bear the ravage, anti-pulling-out force of nails is totally utilized, the safety factor is obviously larger then mode 2, 3, 4, then a conclusion will be drawn that facing of soil nailed wall is a key part to bear soil pressure and resist failure of a slope, the joints between nails and itself should be strengthen, this conclusion is valuable to design and construction engineers, furthermore, anti-shear capability is also important to stability, which result in full utilization of anti-pulling-out force of nails, which can be known. From mode 3 and 4, computing results show no difference in safety factor and distribution of forces of each nail, which means that usually yield limit of nails is enough to resist pulling.

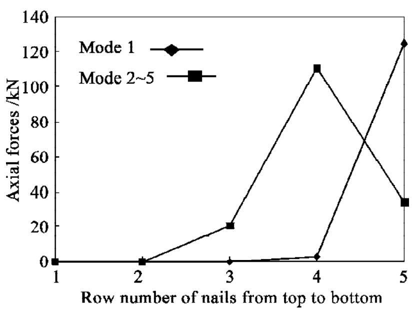
3.2　Cases 2 and 3

This engineering cases are from Zhang's cases[6], and two foundation pits are studied through limit equilibrium, finite element analysis and spot measure. Necessary parameters are listed in table 2. Thickness of facing of two pits is 100 mm, parameters of soils and nails is listed in table 2, and computing results are shown in figures 4 and 5.

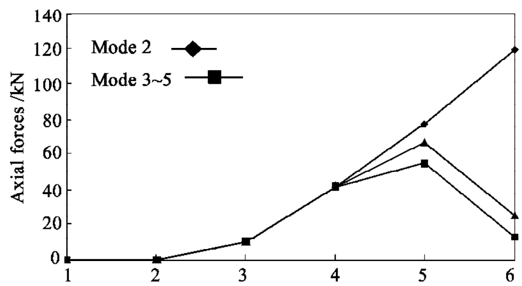
Tab. 2　Soil and nail parameters of two pits

Pit	Depth /m	Slope /°	Spacing /m	Soil parameters			Diameter of bores /mm	Interface cohesion /kPa	Diameter of nails /mm	Yield limit of nails /MPa	Length of nails /m
				C /kPa	ϕ /°	λ /(kN·m^{-3})					
a*	9.0	90	1.8#	3	28	19	150	80	25	310	7.0
b##	9.0	90	1.5#	5	36	21.3	100	60	25	340	7.0

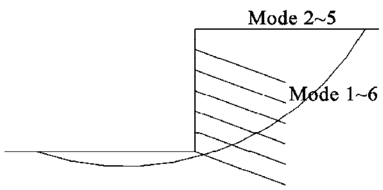
Horizontal spacing is the same as vertical one, *Angle of nails with the horizon is 10 °, ## Angle of nails with the horizon is 20 °。



a)　Represents mode 1 and 6, mode 2~5

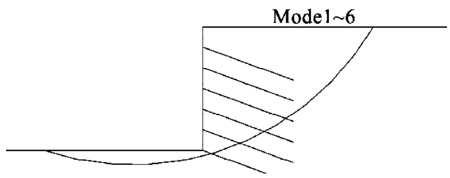


a)　Row number of nails from top to bottom



b)　Location of critical slip surface with different modes

Fig. 4　Computing results of case 2



b)　Location of critical slip surface with different modes

Fig. 5　Computing results of case 3

As far as pit 1 is concerned, safety factors is 1.43, 1.18, 1.19, 1.19, 1.19, 1.43 separately with different modes 1, 2, 3, 4, 5, 6, and of pit 2 is 1.67, 1.59, 1.60, 1.60, 1.60, 1.67, and a characteristics is found that critical failure is in a style of deep slip, with the consideration of facing shear capacity, and assumes that the joints between nails and facing is strong enough to resist ravage, that is to say, the anti-slip force is maximum, soil nailing is safest.

4　Conclusions

Usually in slope stability of soil nailing, anti-pulling-out force of nails is considered ideally, that is to say, only to study the force supplied by passive soil, however, it is reasonable while joints between nails and facing is strong enough, which will result in overestimation of safety. Facing is another important part bearing （下转第49页）